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Substation Fire Protection¹

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BC Hydro

The risk of fire in substations has been historically low, but the possible impacts of a fire can be catastrophic. Fires in substations can severely impact the supply of power to customers and the utility company's revenue and assets. These fires can also create a fire hazard to utility personnel, emergency personnel, and the general public. The recognition of the fire hazards, the risks involved, and the appropriate fire-protection mitigation measures are some of the key considerations for the design and operation of new or existing substations.

This chapter provides an overview to help substation designers identify fire hazards within a substation, identify appropriate fire protection measures, and evaluate the benefit of incorporating these measures. It is only an overview and is not intended to be all-inclusive or to provide all the necessary details to carry out a project. For further details and information on this topic, it is recommended that the designer refer to IEEE 979 [1].

14.1 Fire Hazards

14.1.1 Substation Hazards

The physical objects or conditions that create latent (undeveloped) demands for fire protection are called hazards. Every fire hazard has the following attributes:

¹Some material in this chapter from Delcourt, D., Substation fire protection in *The Electric Power Engineering Handbook*, Grigsby, L.L., Ed., CRC Press, Boca Raton, FL, 2001.

TABLE 14.1 Types and Origins of Substation Fires as Reported by a Major Utility, 1971–1994

Types and Origins of Fires	Percentages
Oil-insulated circuit breakers	14.0
Current transformers	14.0
Power transformers	9.3
Hot work procedures (welding, cutting, and grinding)	9.3
Potential transformers	7.8
Engine-driven generators	7.0
Arson	6.3
Smoking	6.0
Lightning	4.7
Flammable liquid storage or handling	3.1
Terrorism	1.6
Miscellaneous fires	15.8

Source: BC Hydro.

A probability that a fire will actually occur during a specified time interval

The magnitude of a possible fire

The consequence of the potential loss

One of the key steps in the design of new substations and the assessment of existing substations is to identify conditions that are fire hazards. Once the fire hazards of a planned or existing substation are identified, then fire protection measures can be incorporated to eliminate or lessen the fire hazard.

There are a wide range of types and causes of the fires that can occur in substations. The types of fires depend on the equipment and systems used in the stations. Fires involving dc valves, outdoor or indoor oil-insulated equipment, oil-insulated cable, hydrogen-cooled synchronous condensers, or PCB-insulated equipment are usually well documented, and these types of equipment are easily recognized as a fire hazard. There are a number of other substation-specific types of fires that are not as well documented. IEEE 979, “Guide for Substation Fire Protection;” Factory Mutual ‘Data Sheets’; NFPA 851, “Recommended Practice for Fire Protection for Electric Generating Plants and Current Converter Stations” [2]; and CIGRE TF 14.01.04, “Report on Fire Aspects of HVDC Valves and Valve Halls” [3] — provide guidance on other types of fire hazards and fire protection. Also, the Edison Electric Institute’s ‘Suggested Guidelines for Completing a Fire Hazards Analysis for Electric Utility Facilities (Existing or in Design)’ 1981 [4] provides reference guidelines for the fire-hazard analysis process.

Energized electrical cables with combustible insulation and jacketing can be a major hazard because they are a combination of fuel supply and ignition source. A cable failure can result in sufficient heat to ignite the cable insulation, which could continue to burn and produce high heat and large quantities of toxic smoke. Oil-insulated cables are an even greater hazard, since the oil increases the fuel load and spill potential.

The hazard created by mineral-oil-insulated equipment such as transformers, reactors, and circuit breakers is that the oil is a significant fuel supply that can be ignited by an electrical failure within the equipment. Infiltration of water, failure of core insulation, exterior fault currents, and tap-changer failures are some of the causes of internal arcing within the mineral insulating oil that can result in fire. This arcing can produce breakdown gases such as acetylene and hydrogen. Depending on the type of failure and its severity, the gases can build up sufficient pressure to cause the external shell of the transformer tank or ceramic bushings to fail or rupture. Once the tank or bushing fails, there is a strong likelihood that a fire or explosion will occur. A possible explosion could cause blast damage. The resulting oil-spill fire could spread to form a large pool of fire, depending on the volume of oil, spill containment, slope of the surrounding area, and the type of the surrounding ground cover (i.e., gravel or soil). Thermal radiation and convective heating from the oil spill fire can also damage surrounding structures and structures above the fire area.

Substations are exposed to the common industrial fire hazards such as the use and storage of flammable compressed gases, hot work, storage and handling of flammable liquid, refuse storage, presence of heating equipment, and storage of dangerous goods. The local fire codes or NFPA codes can provide assistance in recognizing common fire hazards.

A study was carried on the substation fires reported by a major utility for the period from 1971 to 1994. [Table 14.1](#) shows the types and origins of fires and the percentage for each category. The “miscellaneous fires” category covers a wide range of fires from grass fires to a plastic wall clock failing and catching fire. It is impossible to predict all of the different types of fires that can occur.

14.1.2 Switchyard Hazards

Some of the specific components encountered in substation switchyards that are fire hazards are:

- Oil-insulated transformers and breakers
- Oil-insulated potheads
- Hydrogen-cooled synchronous condensers
- Gasoline storage or dispensing facilities
- Vegetation
- Combustible service building
- Storage of pesticides or dangerous goods
- Storage warehouses
- Standby diesel-generator buildings

The failure of some of the critical components such as transformers and breakers can directly result in losses of revenue or assets. Other switchyard components could create a fire exposure hazard to critical operational components (i.e., combustible service buildings located close to bus support structures or transmission lines). For additional information, see the checklist for the switchyard fire-protection assessment process at the end of this chapter.

14.1.3 Control- and Relay-Building Hazards

A control or relay building can include the following potential hazards:

- Exposed combustible construction
- Combustible finishes
- Emergency generators, shops, offices, and other noncritical facilities in the control buildings
- Batteries and charger systems
- Switchyard cable openings that have not been fire-stopped
- Adjacent oil-insulated transformers and breakers
- High-voltage equipment
- Dry transformers
- Workshops

A fire in any of these components could damage or destroy critical control or protection equipment. Damages could result in a long outage to customers as well as significant revenue losses.

14.1.4 Indoor Station Hazards

Fires in indoor stations are caused by some of the same substation-related hazards as switchyards and control rooms. The impacts of any fires involving oil-insulated equipment, oil-insulated cable, and HVDC (high-voltage dc) valves in an indoor station can result in major fires, with accompanying large asset losses and service disruptions. The basic problems with major fires in indoor stations is that the building will contain the blast pressure, heat, and smoke, and which can result in:

- Blast damage to the building structure (structural failure)
- Thermal damage to the building structure (structural failure)
- Smoke damage to other equipment (corrosion damage)

14.2 Fire Protection Measures

The measures to mitigate or lessen fire hazards are normally called “fire protection measures.” The National Fire Protection Association standards and local building fire codes set the standards for application and design of fire protection. The types of measures can be broken down as follows:

- Life safety
- Passive fire protection
- Active fire protection
- Manual fire protection

14.2.1 Life Safety

Life safety measures generally include the fire protection measures required under the building, fire, or life safety codes. The main objective of these codes is to ensure that:

- The occupants are able to leave the station without being subject to hazardous or untenable conditions (thermal exposure, carbon monoxide, carbon dioxide, soot, and other gases).
- Firefighters are safely able to effect a rescue and prevent the spread of fire.
- Building collapse does not endanger people (including firefighters) who are likely to be in or near the building.

To meet these objectives, fire safety systems provide the following performance elements:

- Detect a fire at its earliest stage.
- Signal the building occupants and/or the fire department of a fire.
- Provide adequate illumination to an exit.
- Provide illuminated exit signs.
- Provide fire-separated exits within reasonable travel distances from all areas of a building. These exits shall terminate at the exterior of the building.
- Provide fire separations between building floors and high-hazard rooms to prevent the spread of fire.
- Provide passive protection to structural components to prevent their failure due to fire exposure.

14.2.2 Passive Fire Protection

Passive measures are static measures that are designed to control the spread of fire and withstand the effects of fire. These measures are the most frequently used methods of protecting life and property in buildings from a fire. This protection confines a fire to a limited area or ensures that the structure remains sound for a designated period of fire exposure. Its popularity is based on the reliability of this type of protection, since it does not require human intervention or equipment operation. Common types of passive protection include fire-stopping, fire separations, equipment spacing, use of noncombustible construction materials, use of low-flame-spread/low-smoke-development rated materials, substation grading, provision of crushed rock around oil-filled equipment, etc.

The degree of passive protection for a building structure would be based on the occupancy of the area and the required structural integrity. The structural integrity of a building is critical in order to preserve life and property. The premature structural failure of a building before the occupants can evacuate or the fire department can suppress the fire is a major concern. Building and electrical codes will provide some of the criteria for structural fire resistance.

IEEE 979 includes recommendations on these measures relative to substation design.

14.2.3 Active Fire Protection

Active fire protection measures are automatic fire protection measures that warn occupants of the existence of fire and extinguish or control the fire. These measures are designed to automatically extinguish or control a fire at an earliest stage without risking life or sacrificing property. The benefits of these systems have been universally identified and accepted by building and insurance authorities. Insurance companies have found significant reduction in losses when automatic suppression systems have been installed.

An automatic suppression system consists of an extinguishing agent supply, control valves, a delivery system, and fire detection and control equipment. The agent supply may be virtually unlimited (such as with a city water supply for a sprinkler system) or of limited quantity (such as with a water tank supply for a sprinkler system). Typical examples of agent control valves are deluge valves, sprinkler valves, and halon control valves. The agent delivery systems are a configuration of piping, nozzles, or generators that apply the agent in a suitable form and quantity to the hazard area (e.g., sprinkler piping and heads). Fire detection and control equipment can be either mechanical or electrical in operation. These systems can incorporate a fire detection means such as sprinkler heads, or they can use a separate fire detection system as part of their operation. These active fire protection systems detect a fire condition, signal its occurrence, and activate the delivery system. Active systems include wet, dry, and pre-action sprinklers, deluge systems, foam systems, and gaseous systems.

Detailed descriptions of each of these systems, code references, and recommendations on application are covered in IEEE 979.

14.2.4 Manual Fire Protection

Manual measures include items such as the various types of fire extinguishers, fire hydrants, hose stations, etc. requiring active participation by staff or the fire department to detect, control, and extinguish a fire. Portable fire equipment is provided for extinguishing incipient-stage fires by building occupants. Since the majority of fires start small, it is an advantage to extinguish them during their incipient stage to ensure that potential losses are minimized.

Detailed descriptions of each of these systems, code references, and recommendations on application are covered in IEEE 979.

14.3 Fire Protection Selection

Fire protection measures can be subdivided into life-safety and investment categories.

14.3.1 Life-Safety Measures

Life-safety measures are considered to be mandatory by fire codes, building codes, or safety codes. As such, the codes mandate specific types of fire protection, with very little flexibility in their selection.

14.3.2 Investment Considerations

Investment-related fire protection is provided to protect assets, conserve revenue, and help maintain service to customers. This type of fire protection is not commonly mandated by legislation but is driven by economic reasons such as asset losses, revenue losses, and the possible loss of customers. Therefore, there is considerable flexibility in the fire risks that are mitigated, the fire protection measures used, whether the risk is offset by purchasing insurance, or whether the risk of a loss is absorbed as a cost of doing business.

The selection of investment-related fire protection can be done based on company policies and standards, insurance engineering recommendations, industry practices, specific codes and standards (IEEE 977 and NFPA 850), or by risk-based economic analysis.

The risk-based economic analysis is the evaluation of the investment measures in relation to the probability of fire, the potential losses due to fire, and the cost of the fire protection measures. This

TABLE 14.2 Probability of Fire for Various Transformer Voltages

Transformer Voltage	Annual Fire Frequency
69 kV	0.00034 fires/year
115–180 kV	0.00025 fires/year
230–350 kV	0.0006 fires/year
500 kV	0.0009 fires/year

Source: IEEE 979, *Guide for Substation Fire Protection*.
With permission.

analysis requires a reasonable database of the probability of fires for the different hazard areas or types, an assessment of the effectiveness of the proposed fire protection measures, an estimate of the fire loss costs, and a fair degree of engineering judgment. The potential losses usually include the equipment loss as well as an assessment of the lost revenue due to the outage resulting from the loss of equipment.

One of the most common risk-based economic analysis types is a benefit/cost analysis. This analysis is calculated using the following equation:

$$\text{benefit / cost ratio} = \frac{\text{annual frequency of fire} \times \text{fire loss costs (assets + revenue)}}{\text{cost of fire protection} \times (1 / \text{effectiveness of fire protection measure})}$$

Normally, this ratio should be greater than one and preferably greater than two. A benefit/cost ratio of two means that the benefit (avoided fire loss costs) is twice the cost of the fire protection. Therefore it is a good investment.

One of the greatest difficulties is to estimate the frequency of fire for the specific hazards. Some companies have extensive fire loss histories and loss databases. These databases can be used to estimate specific fire frequencies, but the results may be poor due to the small statistical sample size based on the company's records. There are a number of other databases and reports that are in the public domain that provide useful data (i.e., NFPA data shop, EPRI Fire Induced Vulnerability Evaluation Methodology, and IEEE 979 Transformer Fire Survey). Table 14.2 shows the estimated probability of fire from the IEEE 979 Transformer Fire Survey.

Once the potential financial loss due to a fire has been calculated, the designer should input costs and effectiveness of any proposed fire protection measure into the benefit/cost equation and determine the B/C ratio. If the B/C ratio is less than one, provision of the fire protection measure is not an acceptable investment.

14.3.3 Example of a Risk-Based Economic Analysis

The following is a simplified example of an analysis:

- A substation has four 138-kV single-phase oil-insulated transformers. One of these transformers is a spare and is located remote from the others. The load supplied by these transformers is 25 MW. A water-spray deluge system is being considered to suppress or control a fire in the transformers. The deluge system is expected to protect the adjacent transformers, but not save the transformer that catches fire. The estimated cost of a deluge system for all three transformers is \$60,000. The individual transformers have a replacement value of \$300,000.
- The utility's chief financial officer questions whether this is a good investment.
- The company uses a discount rate of 10% and requires that all investments have a benefit/cost ratio greater than two. The assigned value of energy is \$25/MW. The standard amortization period is 25 years.
- The annual frequency of fire for a single 138-kV transformer is estimated as 0.00025 fires/year. Therefore, the combined frequency for the three transformers is 0.00075 fires/year.

- The estimated effectiveness of the deluge system protecting the adjacent transformers is 0.9. The deluge system will not save the transformer in which the fire originates; it is assumed to be a total loss.
- The fire is assumed to originate in the center transformer in the bank of three single-phase transformers. It is assumed that in the absence of suppression, the fire will spread to destroy the two adjacent transformers. The spare transformer is not affected because it is remote from the other transformers.
- The estimated station outage period for this scenario is the difference between the outage time to replace all three transformers (a fire in the center transformer could destroy all three transformers) and the outage time to replace the center transformer (assuming the deluge system will protect the adjacent transformers). The outage time to replace a single unit is five days and to replace three units is 40 days. Therefore, the expected outage loss period is 35 days.
- The expected lost revenue is $35 \text{ days} \times 24 \text{ h/day} \times 25 \text{ MW/h} \times \$25/\text{MW} = \$525,000$.
- The estimated annual revenue and equipment loss costs = (composite annual fire frequency) $\times$ (revenue loss for the station outage period + replacement value of the adjacent transformers) = $(0.00075 \text{ fires/year}) \times [\$525,000 + (2 \times \$300,000)] = \$843.75/\text{year}$.
- The net present value of the annual revenue and equipment losses for the 25-year amortization period at a discount rate of 10% = \$7659.
- The benefit/cost ratio = $\$7659 / [\$60,000 \times (1.0/0.9)] = 0.115$.
- Example conclusion: The calculated benefit/cost ratio of 0.115 is considerably less than the minimum required ratio of two. The proposal to install deluge protection should be rejected, since it is not economical. Other fire protection measures could be considered, or the risk could be transferred by purchasing insurance to cover the possible loss of the assets (transformers) and the revenue. These other measures can also be analyzed using this methodology for economic risk analysis.

It should be noted that the above example does not include societal costs, loss of reputation, and possible litigation.

14.4 Conclusion

The assessment of the hazards involved with an existing or planned substation and the selection of the most appropriate fire protection are the best ways to ensure that the power supply to customers, company revenue, and company assets are protected from fire. Substation, switchyard, and control-building fire-protection-review checklists are presented at the end of this chapter to aid in the assessment process. The IEEE Guide for Substation Fire Protection, Std. 979, provides an excellent guide to the assessment process.

References

1. Institute of Electrical and Electronics Engineers, IEEE Guide for Substation Fire Protection, IEEE Std. 979-1994, IEEE, Piscataway, NJ, 1994.
2. National Fire Protection Association, Recommended Practice for Fire Protection for Electric Generating Plants and Current Converter Stations, NFPA 851, NFPA, Boston, 1996.
3. CIGRE, Report on Fire Aspects of HVDC Valves and Valve Halls, TF 14.01.04, CIGRE, Paris, 1992.
4. Edison Electric Institute, Suggested Guidelines for Completing a Fire Hazards Analysis for Electric Utility Facilities (Existing or in Design), Edison Electric Institute, Washington, D.C., 1981.

Substation Control Building Fire-Protection-Review Checklist

Risk Assessment

- Review the criticality of the control room and building fire loss to the substation operation and asset base
- Review the historical frequency of fire in control buildings

Life-Safety Assessment

- Review the control-room layout to ensure that the room has a minimum of two outward swinging exit doors
- Ensure that the travel distance from any area within the control building to an exit does not exceed 100 ft
- Ensure that exit signs are installed at each exit door
- Review that emergency lighting is provided that will provide a minimum lighting level of 10 lx at the floor, along the exit paths
- Review the size and number of stories of the building to ensure proper exits are provided such that maximum travel distances to the exits do not exceed 100 ft
- Determine if there are any building- or fire-code requirements for the installation of a fire detection system

Fire Protection Assessment

- Review the availability of a fire department response to the site
- Review the availability of fire-fighting water supply at or adjacent to the site
- Review the adequacy of any existing control-building fire protection
- Review criticality of control-building equipment, hazards involved, and response time of station personnel and the fire department
- Determine the type of detection that will provide an acceptable very early detection (air sampling detection) to detect a fire at a very early stage (small electronic component failure, arcing) or at an early stage with smoke detection (photoelectric detection) to detect a fire at a smoldering or small flame stage
- Determine the type of fire suppression system that will provide an acceptable level of equipment losses and outages (i.e., gaseous suppression systems to suppress a fire at an early stage [component loss] or sprinkler protection to suppress a fire at the stage where the loss would be restricted to a single control cabinet)
- Review the occupied hours of the building and the ability of site personnel to safely extinguish a fire with portable fire equipment
- Determine the levels of portable fire equipment required by the local fire code and that equipment is suitable for safe staff operation

Hazard Assessment

- Review the other uses (shops, offices, storage, etc.) within the control building and their exposure to the critical substation equipment
- Review the use of combustible construction in the control building (i.e., exterior surfaces and roofs)
- Review the use of combustible interior surface finishes in the control room and ensure that the surface finishes have a flame spread rating of less than 25

- Review the combustibility of any exposed cable used in the building to ensure that it meets the requirements of IEEE 383
- Review the control-room separation walls to other occupancies to ensure that the walls have a fire resistance rating of a minimum of 1 h

Substation Switchyard Fire Protection Assessment Process

Risk Assessment

- Determine the initial electric equipment layout and equipment types
- Review the criticality of the various pieces of equipment
- Review types of insulating fluid used and their flammability
- Review the historical frequency of fire for the various types of equipment
- Review the availability of a fire department response to the site
- Review the availability of a fire-fighting water supply at or adjacent to the site
- Review the adequacy of any existing substation fire protection

Radiant Exposure Assessment

- Review the spacing between individual single-phase transformers and breakers with IEEE 979 Table 1
- Review the spacing between large three-phase transformers, banks of single-phase transformers, or groups of breakers with IEEE 979 Table 1
- Review the spacing of oil-filled equipment with respect to substation buildings with IEEE 979 Table 2. Note that the presence of combustible surfaces and unprotected windows on exposed surfaces of the buildings may require detailed thermal radiation calculations or the application of safety factors to the table distances. The Society of Fire Protection Engineers publication *Engineering Guide for Assessing Flame Radiation to External Targets from Pool Fires* can be used as a reference for detailed thermal radiation calculations.
- Review the distances between oil-filled equipment and the property line. Note that combustible vegetation and building structures beyond the property line of the substation may be exposed to high enough heat fluxes to ignite combustible surfaces. Detailed thermal radiation calculations should be considered.
- Review the use of the various methods of fire protection discussed in IEEE 979 that will address the hazard determined in the radiant-exposure assessment, such as changing the type of equipment and insulating fluid used, increased spacing, provision of gravel ground cover, oil containment, fire barriers, and automatic water-deluge fire protection

Fire Spread Assessment

- Is the surface around oil-filled equipment pervious (gravel) or impervious? Use of 12-in.-thick gravel ground covers will suppress the flames from a burning oil-spill fire. Impervious surfaces can allow the burning oil to form a large pool fire, which will increase the heat flux to adjacent equipment and structures.
- Is there any oil containment in place around the oil-filled equipment? Oil containment can contain pool fires and prevent their spread.
- Does the grade surrounding the oil-filled equipment slope toward the equipment or away from the oil-filled equipment toward adjacent oil-filled equipment, cable trenches, drainage facilities,

or buildings? The burning oil released from ruptured oil-filled equipment can spread for significant distances if the ground surrounding the equipment has a slope greater than 1%.

- Review the use of the various methods of fire protection discussed in IEEE 979 that will address the hazard determined in the fire spread assessment. These methods include the following:
 - Changing the type of equipment and insulating fluid used
 - Increasing the spacing of gravel ground cover
 - Provision of oil containment
 - Changing the grade surrounding the equipment
 - Use of liquid-tight noncombustible cable trench cover adjacent to oil-filled equipment
 - Fire-stopping of cable-trench entries into control buildings
 - Use of automatic water-deluge fire protection